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Is lumpy investment really irrelevant for the business cycle?

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Abstract

New-Keynesian (NK) models can only account for the dynamic effects of monetary policy shocks if it is assumed that aggregate capital accumulation is much smoother than it would be the case under frictionless firm-level investment, as discussed in Woodford (2003, Ch. 5). We find that lumpy investment, when combined with price stickiness and market power of firms, can rationalize this assumption. Our main result is in stark contrast with the conclusions obtained by Thomas (2002) in the context of a real business cycle (RBC) model. We use our model to explain the economic mechanism behind this difference in the predictions of RBC and NK theory.

Keywords: Lumpy Investment, Sticky Prices.

JEL Classification: E22, E31, E32

1 Introduction

What are the consequences of lumpy firm-level investment for business cycle dynamics? This question has been studied by Thomas (2002) in the context of a real business cycle model with perfect competition and fully flexible prices. Her analysis implies that the equilibrium dynamics with lumpy firm-level investment are strikingly similar to the ones associated with a specification where investment at the firm level is *frictionless*.[1]

In the present paper we seek to understand the role of lumpy firm-level investment in a dynamic New Keynesian (NK) model. This is important because if the above mentioned result by Thomas (2002) were robust in the context of NK models then this would cast serious doubts on the extent to which these models are useful for the analysis of the consequences of monetary policy, which is the hallmark of NK theory. The reason is that NK models featuring *frictionless* endogenous capital accumulation cannot explain the consequences of monetary policy shocks, as Casares and McCallum (2000) and Woodford (2003, Ch. 5) have shown. In order to render NK models capable of avoiding this problem it is common practice to assume some convex capital adjustment cost.[2] This is clearly unrealistic in the light of the microevidence on investment behavior. More importantly, it is unclear if the smoothness in aggregate capital accumulation, which is needed to render NK models consistent with the empirical evidence on monetary policy shocks, can be obtained with lumpy firm-level investment.

We find that our NK model with lumpy firm-level investment is equivalent to an otherwise identical specification featuring a *convex capital adjustment cost* at the firm level. This is due to the presence of price stickiness and imperfect competition

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[1] This result is robust with respect to the inclusion of idiosyncratic productivity shocks at the firm-level, as has been recently shown in Khan and Thomas (2005). A similar quasi-irrelevance result has also been obtained in Veracierto (2002). However, the focus of his analysis is the role of firm-level irreversibility in investment for aggregate fluctuations.

[2] See, e.g., Christiano et al.(2005), Smets and Wouters (2003), and Woodford (2003, Ch. 5).

in goods markets. Our main finding is that aggregate smoothness in capital accumulation is increasing with both the degrees of price stickiness in the economy and the market power of firms. Let us put this result into perspective. Thomas (2002) notes that if prices are fixed then "there are both quantitative and qualitative changes in the response of aggregate investment relative to the neoclassical benchmark". This way she confirms earlier results which have been obtained in the context of partial equilibrium models.[3] Our main contribution in the present paper is therefore the following. We explain the effects of an empirically plausible degree of price stickiness in goods markets on aggregate capital accumulation, and we disentangle this from the consequences of imperfect competition, which we identify as an independent factor underlying the aggregate relevance of lumpy firm-level investment.

The remainder of the paper is organized as follows: Section 2 outlines our baseline model with lumpy firm-level investment. We employ the Calvo mechanism both for modeling price stickiness, as it is the standard in a large body of literature, and for modeling lumpiness in investment, as has been originally proposed by Kiyotaki and Moore (1997). In Section 3 we present and discuss our results. Section 4 concludes.

2　The model economy

In this section we establish the equivalence between a NK model with lumpy investment and an alternative specification featuring a convex capital adjustment cost at the firm level.[4] This equivalence holds for any source of aggregate uncertainty and regardless of the particular rule assumed for the conduct of monetary policy. We

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[3]See, e.g., Caballero and Engle (1999) and Caballero (1999).

[4]Assuming a convex capital adjustment cost at the firm level in a model with staggered price setting has been originally proposed in Woodford (2003, Ch. 5). Recently, other contributions that use this set of assumptions have mushroomed. See, e.g., Altig. et al. (2004), Christiano (2004), Sveen and Weinke (2004, 2005), and Woodford (2004, 2005), among many others. One corollary of the equivalence result in the present paper is that the conclusions obtained in this strand of the literature do not appear to hinge on empirically unappealing assumptions regarding investment behavior on the part of firms.

therefore leave these two aspects of our model unspecified and focus on the behavior of firms and households. Firms are assumed to act under monopolistic competition. The features of sticky prices and lumpy investments are introduced into the model by invoking the Calvo (1983) assumption both for price setting- and for investment decisions, i.e. we assume two exogenous adjustment probabilities, one for each decision. This way we capture the fact that firms change prices or adjust their capital stocks only infrequently. Households are modelled in a standard way. We turn to this next.

2.1   Households

Households have access to a complete set of financial securities and supply labor in a perfectly competitive market. A representative household maximizes expected discounted utility:

$$E_t \sum_{k=0}^{\infty} \beta^k U\left(C_{t+j}, N_{t+j}\right), \tag{1}$$

where $U\left(\cdot\right)$ is period utility, C_t is a Dixit-Stiglitz composite consumption index, and N_t are hours worked. The period utility function is assumed to be given by:

$$U\left(C_t, N_t\right) = \frac{C_t^{1-\sigma}}{1-\sigma} - \frac{N_t^{1+\phi}}{1+\phi}, \tag{2}$$

where parameters σ and ϕ are, respectively, the inverse of the household's intertemporal elasticity of substitution and the inverse of the household's labour supply elasticity.

The consumption aggregate is defined as follows:

$$C_t = \left(\int_0^1 C_t\left(i\right)^{\frac{\varepsilon-1}{\varepsilon}} di\right)^{\frac{\varepsilon}{\varepsilon-1}} \quad \text{for } i \in [0,1], \tag{3}$$

where parameter $\varepsilon > 1$ measures the elasticity of substitution between the different

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types of goods.

The household's maximization is subject to a sequence of budget constraints which take the following form:

$$\int \left[P_t\left(i\right) C_t\left(i\right) \right] di + E_t \left\{ Q_{t,t+1} D_{t+1} \right\} \leq D_t + P_t W_t N_t + T_t. \tag{4}$$

Here $P_t\left(i\right)$ is the price of type i goods, $Q_{t,t+1}$ denotes the stochastic discount factor for random nominal payments, D_{t+1} is the nominal payoff associated with the portfolio held at the end of period t, and T_t denotes profits resulting from ownership of firms.

Optimizing behavior on the part of households implies the following consumption demand function for each type of goods:

$$C_t^d\left(i\right) = \left(\frac{P_t\left(i\right)}{P_t} \right)^{-\varepsilon} C_t, \tag{5}$$

where the price index P_t is given by:

$$P_t = \left(\int P_t\left(i\right)^{1-\varepsilon} di \right)^{\frac{1}{1-\varepsilon}}. \tag{6}$$

The remaining first order conditions read:

$$C_t^\sigma N_t^\phi = W_t, \tag{7}$$

$$\beta \left(\frac{C_{t+1}}{C_t} \right)^{-\sigma} \left(\frac{P_t}{P_{t+1}} \right) = Q_{t,t+1}, \tag{8}$$

where $R_t^{-1} = E_t Q_{t,t+1}$ is the price of a risk-less one-period bond. The first equation is the labor supply equation, whereas the second one is a standard intertemporal optimality condition.

2.2 Firms

There is a continuum of firms indexed on the unit interval. Each firm $i \in [0,1]$ is assumed to produce a differentiated good $Y_t(i)$ using the following Cobb-Douglas production function:

$$Y_t(i) = N_t(i)^{1-\alpha} K_t(i)^{\alpha}, \qquad (9)$$

where $\alpha \in [0,1]$ is the capital share. The variables $N_t(i)$ and $K_t(i)$ denote, respectively, hours used and capital holdings of firm i in period t.

Cost minimization by firms and households implies that demand for each individual good i in period t can be written as follows:

$$Y_t^d(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\varepsilon} Y_t^d, \qquad (10)$$

where Y_t^d denotes aggregate demand at time t, which is given by:

$$Y_t^d = C_t + K_{t+1} - (1-\delta) K_t, \qquad (11)$$

and $K_t \equiv \int_0^1 K_t(i)\, di$ defines aggregate capital holdings.

Each period a measure $1 - \theta_p$ of randomly selected firms change their prices and the rest of the firms keep their prices constant. We model lumpy investment in an analog way. In order to capture the fact that firms adjust their capital stocks infrequently we assume that each of them invests in a certain time period with probability $1 - \theta_k$. The adjustment probability is independent of the time elapsed since the last investment and of whether the firm is allowed to change its price or not. The latter assumption is used to capture the fact that the economic reasons giving rise to infrequent adjustment of prices and capital holdings are likely to be different from each other. Moreover, to simplify the analysis, we assume that the investment lottery is drawn after the price-setting lottery. Hence, firms have to post

their prices before they get to know the outcome of the investment lottery.

Let us consider a price setter's problem. Given its time t capital stock, $K_t(i)$, a price setter i chooses contingent plans for $\left\{P_{t+j}^*(i), K_{t+j+1}^*(i), N_{t+j}(i)\right\}_{j=0}^{\infty}$ in order to maximize the following:[5]

$$\sum_{j=0}^{\infty} E_t\left\{Q_{t,t+j}\left[Y_{t+j}^d(i)P_{t+j}(i) - P_{t+j}\left(W_{t+j}N_{t+j}(i) - \left(K_{t+j+1}(i) - (1-\delta)K_{t+j}(i)\right)\right)\right]\right\}$$

s.t.

$$
\begin{aligned}
Y_{t+j}^d(i) &= \left(\frac{P_{t+j}(i)}{P_{t+j}}\right)^{-\varepsilon} Y_{t+j}^d, \\
Y_{t+j}^d(i) &\leq N_{t+j}(i)^{1-\alpha} K_{t+j}(i)^{\alpha}, \\
P_{t+j+1}(i) &= \begin{cases} P_{t+j+1}^*(i) & \text{with prob. } (1-\theta_p) \\ P_{t+j}(i) & \text{with prob. } \theta_p \end{cases} \\
K_{t+j+1}(i) &= \begin{cases} K_{t+j+1}^*(i) & \text{with prob. } (1-\theta_k) \\ K_{t+j}(i) & \text{with prob. } \theta_k \end{cases}
\end{aligned}
$$

The last restriction reflects our assumption regarding the timing of the two lotteries for price setting and for investment. Moreover, it is implicit in this formulation that a firm which is not allowed to make an investment decision in a given period is nevertheless assumed to keep its capital constant by paying for the depreciation. This way we capture the fact that firms appear to engage continuously in some small maintenance investment, as Doms and Dunne (1998) report for the U.S. economy.

The first order condition for price setting is given by:

$$\sum_{j=0}^{\infty} \theta_p^j E_t\left\{Q_{t,t+j}Y_{t+j}^d(i)\left[P_t^*(i) - \mu P_{t+j}MC_{t+j}(i)\right]\right\} = 0, \tag{12}$$

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[5]A firm j that cannot change its price at time t solves the same problem, except for the fact that it takes $P_t(j)$ as given.

where $\mu \equiv \frac{\varepsilon}{\varepsilon-1}$ denotes the frictionless mark-up over marginal costs, and $MC_t(i)$ denotes the real marginal cost of firm i in period t. The latter is given by:

$$MC_t(i) = \frac{W_t}{MPL_t(i)}, \tag{13}$$

where $MPL_t(i)$ denotes the marginal product of labour of firm i in period t. Equation (12) reflects that prices are chosen in a forward-looking manner, i.e. taking into account not only the current but also the future marginal cost over the expected lifetime of a chosen price.

The first order condition for capital accumulation reads:

$$\sum_{j=0}^{\infty} \theta_k^j E_t \left\{ Q_{t,t+j} \left[P_{t+j} - Q_{t+j,t+j+1} P_{t+j+1} \left(MS_{t+j+1}(i) + (1-\delta) \right) \right] \right\} = 0 \tag{14}$$

where $MS_{t+1}(i)$ denotes the reduction in firm i's real labor cost associated with having one additional unit of capital in place in period $t+1$. The following relationship holds true:

$$MS_t(i) = W_t \frac{MPK_t(i)}{MPL_t(i)}, \tag{15}$$

where $MPK_t(i)$ denotes the marginal product of capital of firm i in period t. Equation (14) shows that firms invest in a forward-looking manner, i.e. taking into account not only the current but also the future marginal return to capital over the expected lifetime of a chosen capital stock.

2.3 Market Clearing

Clearing of the labor market requires that hours worked, N_t, are given by the following equation, which holds for all t:

$$N_t = \int_0^1 N_t(i) \, di. \tag{16}$$

8

Finally, market clearing for each variety i requires at each point in time:

$$Y_t(i) = Y_t^d(i). \tag{17}$$

2.4 Linearized Equilibrium Conditions

We restrict attention to a linear approximation around a zero inflation steady state. In what follows lower case letters denote the log deviation of the original variable from its steady state value.

2.4.1 Households

From the household's problem we obtain, respectively, an Euler equation and a labor supply equation. They read:

$$c_t = E_t c_{t+1} - \frac{1}{\sigma}(i_t - E_t \pi_{t+1} - \rho), \tag{18}$$

$$w_t = \phi n_t + \sigma c_t, \tag{19}$$

where parameter $\rho \equiv -\log \beta$ is the time discount rate, $i_t \equiv \log R_t$ denotes the time t nominal interest rate, and $\pi_t \equiv \log\left(\frac{P_t}{P_{t-1}}\right)$ is time t inflation.

2.4.2 Firms

We follow Woodford (2004) and derive both the law of motion of aggregate capital and the inflation equation by employing the method of undetermined coefficients. They are given by:

$$\Delta k_{t+1} = \beta E_t \Delta k_{t+2} + \frac{1}{\eta_l}\{(1 - \beta(1 - \delta)) E_t ms_{t+1} - (i_t - E_t \pi_{t+1} - \rho)\} \tag{20}$$

$$\pi_t = \beta E_t \pi_{t+1} + \kappa_l \, mc_t, \tag{21}$$

9

where Δ is the first-difference operator and η_l and κ_l are parameters which are computed numerically. Moreover, $MS_t \equiv \int_0^1 MS_t(i)\, di$ denotes the average time t real marginal savings in labor costs and $MC_t \equiv \int_0^1 MC_t(i)\, di$ is average real marginal cost as of that period.[6]

Aggregating and log-linearizing the production functions of individual firms (9) results in:

$$y_t = \alpha k_t + (1-\alpha)\, n_t, \tag{22}$$

where $Y_t \equiv K_t^\alpha N_t^{1-\alpha}$ is aggregate production, up to the first order.

2.4.3 Market clearing

Aggregating and log-linearizing the goods market clearing condition for each variety (17), and invoking (9) and (11), we obtain:

$$y_t = \zeta c_t + \frac{1-\zeta}{\delta}\left[k_{t+1} - (1-\delta)\, k_t\right], \tag{23}$$

where $\zeta \equiv 1 - \frac{\delta\alpha}{\mu(\rho+\delta)}$ denotes the steady state consumption to output ratio, and $\frac{(1-\zeta)}{\delta}$ is the steady state capital to output ratio.

2.5 The Convex Capital Adjustment Cost Case

In what follows, we consider a benchmark model featuring a convex capital adjustment cost at the firm level, as proposed by Woodford (2003, Ch. 5). He assumes the following restriction on capital accumulation:

$$I_t(i) = I\left(\frac{K_{t+1}(i)}{K_t(i)}\right) K_t(i), \tag{24}$$

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[6]For a detailed derivation of last the two equations in the text, see the Appendix.

where $I_t(i)$ denotes the amount of the composite good which needs to be purchased by firm i at time t in order to change its capital stock form $K_t(i)$ to $K_{t+1}(i)$ in the next period. Moreover, function $I(\cdot)$ is assumed to satisfy the following: $I(1) = \delta$, $I'(1) = 1$, and $I''(1) = \eta_c$. Parameter $\eta_c > 0$ measures the convex capital adjustment cost in a log-linear approximation to the equilibrium dynamics.

We find that the linearized equilibrium conditions implied by the benchmark model are identical to the ones associated with the lumpy investment model, except for the inflation equation and the law of motion of capital. The latter two equations take the following form:

$$
\begin{aligned}
\Delta k_{t+1} &= \beta E_t \Delta k_{t+2} + \frac{1}{\eta_c} \left\{ (1 - \beta(1-\delta)) E_t ms_{t+1} - (i_t - E_t \pi_{t+1} - \rho) \right\} \quad (25)\\
\pi_t &= \beta E_t \pi_{t+1} + \kappa_c \, mc_t, \quad (26)
\end{aligned}
$$

where κ_c is to be computed numerically.[7]

A comparison of the last two equations with their counterparts (20) and (21) in the lumpy investment model reveals that a model featuring a convex capital adjustment cost at the firm level is equivalent to our specification with lumpy investment: for any given value of the lumpiness parameter, θ_k, there exists a value of the convex adjustment parameter, η_c, such that the two laws of motion of capital implied by the two models are identical. Moreover, the two associated inflation equations coincide for this choice of η_c. This makes it possible to compare our model with the convex capital adjustment cost benchmark case in a particularly clean way. We turn to this next.

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[7] For a detailed derivation of the last two equations in the text see, e.g., Woodford (2004).

3 Simulation Results

3.1 Calibration

The period length is one quarter. Table 1 shows the baseline calibration for the lumpy investment model.

Table 1: Baseline Calibration

σ	ε	α	β	ϕ	θ_p	θ_k
2	11	0.36	0.99	1	0.75	0.915

The values assigned to parameters σ, ε, α, β, ϕ, and θ_p are standard.[8] The baseline value of the lumpiness parameter, θ_k, is 0.915. This appears to be in line with the micro evidence on plant-level investment reported by Doms and Dunne (1998). They use U.S. data on $13,700$ manufacturing plants over the 17 year period 1972 to 1988. For each plant they establish a rank distribution of capital growth rates and compute the associated mean and median over all firms for each rank. They find that "many plants experience a few periods of intense capital growth and many periods of relatively small capital adjustment: of the 16 capital growth rate ranks, 12 possess means or medians between -10 and +10%". Moreover they report that plants choose on average every second year to change their capital holdings by at least 5%. We therefore take $\theta_k \in (0.89, 0.94)$ to be an empirically plausible range for the lumpiness parameter since values in this interval imply that firms invest on average about every 2 to 4 years. This means that we interpret the "relatively small capital adjustment" as variation in maintenance.[9] Our choice of the baseline value for the lumpiness parameter is simply the midpoint of the interval.

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[8]See, e.g., Sveen and Weinke (2005) and the references herein.

[9]Variation in maintenance could be entertained in our theoretical model by allowing the depreciation rate to be stochastic.

3.2 Results

Can lumpiness in firm-level investment be reconciled, under empirically plausible assumptions, with the degree of smoothness in aggregate capital accumulation which is needed to render NK models capable of explaining the dynamic effects of monetary policy shocks? Our answer is yes. A value of about 3 for parameter η_l is needed in order to account for the smooth response of aggregate demand in response to monetary policy shocks, as Woodford (2003, Ch. 5) argues in the context of a model featuring a convex capital adjustment cost at the firm level. Given the equivalence between his model and our specification with lumpy firm-level investment we can ask what is the corresponding value of the lumpiness parameter needed to entertain this level of aggregate smoothness in capital accumulation and whether or not this value falls in the interval that we consider to be empirically plausible. We show the result in Figure 1: Woodford's preferred calibration of the smoothness in aggregate capital accumulation falls well in the empirically plausible range. Specifically, $\eta_l = 3$ is associated with $\theta_k = 0.924$ if the remaining parameters are held constant at their baseline values.

This result is in stark contrast with the predictions of a real business cycle (RBC) model. In the latter case the implied equilibrium dynamics with lumpy investment are strikingly similar to the ones associated with a specification where investment at the firm level is *frictionless*, as shown in Thomas (2002). What is the economic reason for this difference between RBC and NK theory? Our answer is that price stickiness and market power of firms, two features that are absent in a RBC model, affect the smoothness of aggregate capital accumulation with lumpy firm-level investment. The intuition is as follows. With lumpy investment the dynamics of aggregate capital accumulation are driven by the decisions of only a *fraction* of firms.[10] These firms internalize the consequences of their investment decisions for their future ex-

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[10]This is the crucial difference with respect to the convex adjustment cost case where it is assumed that *all* firms can choose to adjust their capital holdings at each point in time.
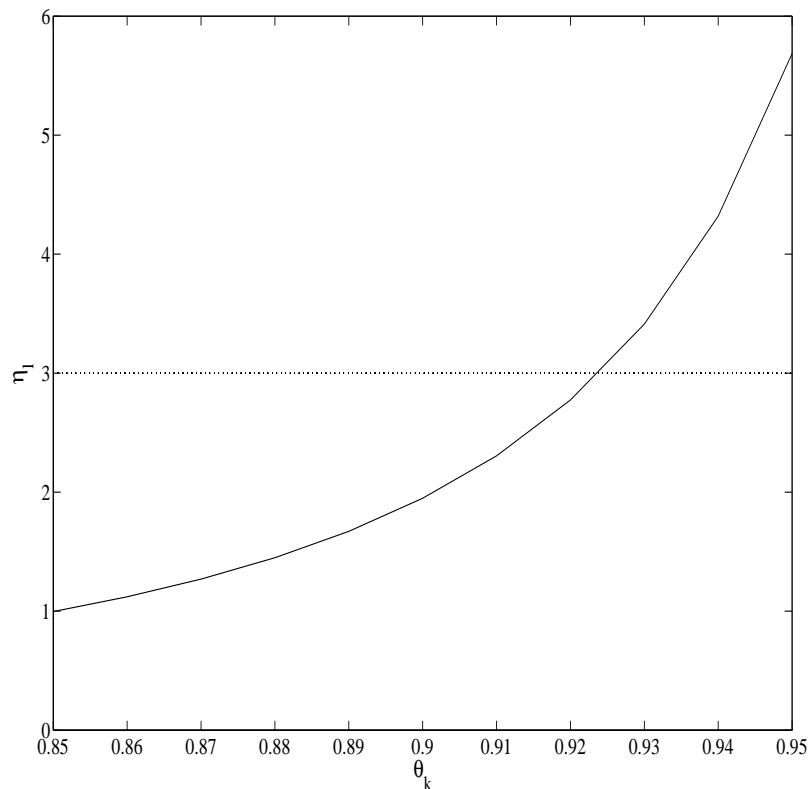
Figure 1: Firm-level lumpiness and aggregate smoothness in capital accumulation.

pected marginal savings. In particular, the currently investing firms foresee that an increase in the economy's capital stock (resulting from their investment decisions) is associated with a decrease in their expected future marginal savings. This means that in response to an increase in the *economywide* average marginal savings the currently investing firms will choose to limit the size of their investment if the associated decrease in their own marginal savings is large.[11] The extent to which the marginal savings in the group of currently investing firms decrease if the capital stock is increased depends in turn on the price setting behavior. The latter is affected by the price stickiness and market power of firms in the economy. We turn to this next. First, we analyze the role of price stickiness if the remaining parameters are held constant at their baseline values. The results are shown in Figure 2.

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[11] The intuition is similar to the one developed by Sbordorne (2002) and Galí et al. (2001) in order to explain the difference in price setting behavior under constant and decreasing returns to scale.
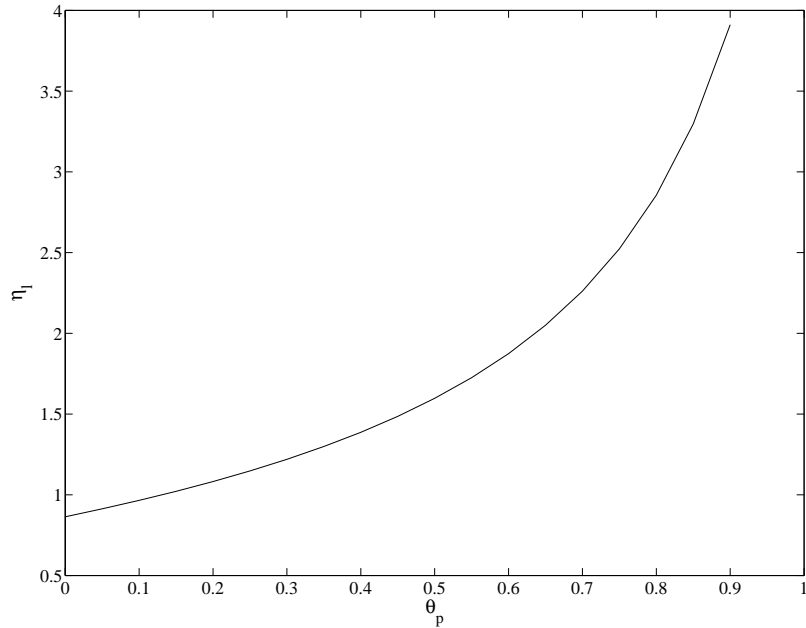
Figure 2: Price stickiness and aggregate smoothness in capital accumulation.

A decrease in the value assigned to parameter θ_p results in a decrease of smoothness in aggregate capital accumulation, as measured by the associated change in the value of parameter η_l. The intuition is simple. With more flexible prices the firms currently choosing to increase their capital holdings are more likely to be able to create additional demand (by decreasing their prices) over the expected lifetimes of their chosen capital stocks. This increases their marginal returns to capital and hence the investing firms are more willing to invest in response to an increase in the average marginal savings. Second, we analyze the role of monopolistic competition under the assumption of perfectly flexible prices. Again, all the remaining parameters are held constant at their baseline values. The results are shown in Figure 3.
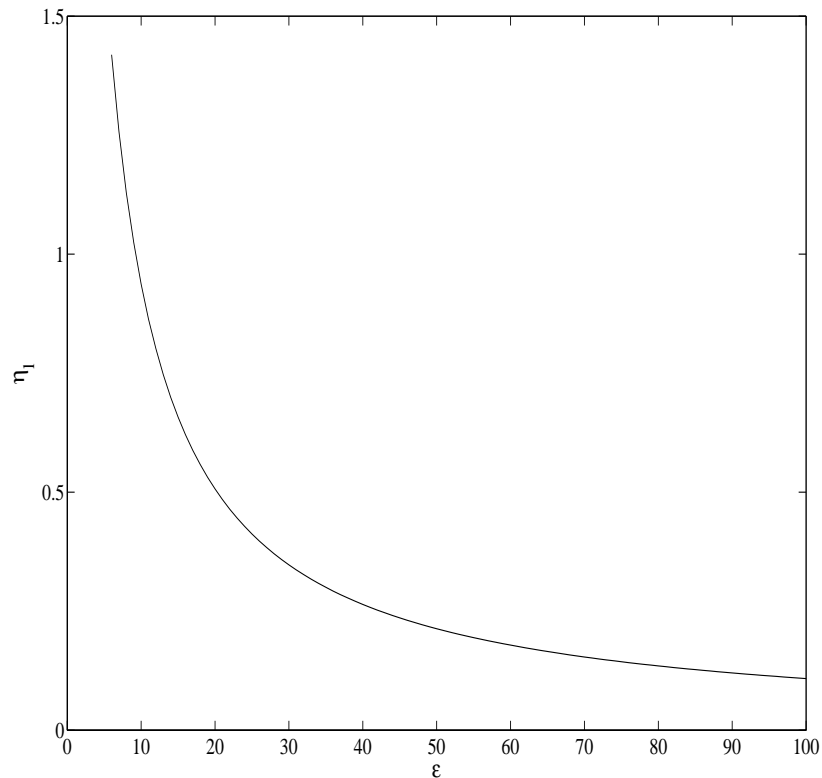
Figure 3: Market power and aggregate smoothness in capital accumulation.

An increase in the value assigned to parameter ε, which is inversely related to the market power of firms, is associated with a decrease in parameter η_l. In a more competitive economy a price change has a larger impact on a firm's demand. Therefore the investing firms can take better advantage of the additional productive capacity. This makes them less reluctant to change their capital stocks in response to an increase in the average marginal savings.

Finally, we turn off the features of price stickiness and monopolistic competition in our model and compare the results with those obtained in Thomas (2002). In the absence of price stickiness and monopolistic competition the linearized equilibrium dynamics of our lumpy investment economy are exactly identical to the ones implied by frictionless investment. This can be seen by inspecting the reduced form

parameter η_l in the flexible price case. It is given by:

$$\eta_l = \frac{\theta_k}{(1 - \theta_k)(1 - \beta\theta_k)} \frac{1 - \beta(1 - \delta)}{1 - \alpha + \varepsilon\alpha}$$

Our model therefore implies results in the spirit of Thomas (2002), if the New-Keynesian features are turned off.

4   Conclusion

Viewed through the lens of a RBC model firm-level lumpy investment appears to be irrelevant for business cycle dynamics: the implied equilibrium dynamics are almost identical to the ones associated with the alternative assumption of frictionless firm-level investment. This has been shown in Thomas (2002). However, in the NK literature it is typically assumed that aggregate capital accumulation is smoother than it would be if investment at the firm level were frictionless. Woodford (2003, Ch. 5) argues that this assumption is crucial for otherwise NK models could not account for the dynamic effects of monetary policy shocks. Can the required smoothness of aggregate capital accumulation be rationalized under the empirically plausible assumption of lumpy firm-level investment? Our answer is yes. In fact, our NK model with lumpy investment is equivalent to its counterpart featuring a convex capital adjustment cost at the firm level. Importantly, the lumpy investment model implies that empirically plausible parameter values result in aggregate smoothness of capital accumulation of the kind that is needed to render NK models capable of explaining the dynamic effects of monetary policy shocks. Moreover, for any given parametrization of lumpiness, the resulting smoothness in aggregate capital accumulation increases with the degrees of price stickiness and monopolistic competition. We use our model to explain why and how price stickiness and market power of firms affect the aggregate smoothness of capital accumulation.

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Appendix: Inflation and Capital Dynamics with Lumpy Investment

In order to find the inflation equation and the law of motion of the aggregate capital stock for our lumpy investment model we follow Woodford (2004) and apply the method of undetermined coefficients. First, we combine (12) with (13) and (14) with (15). Log-linearizing and rearranging the resulting equations gives:

$$
\begin{aligned}
\widehat{p}_t^*(i) &= \sum_{j=1}^{\infty} (\beta\theta_p)^j E_t \pi_{t+j} + \frac{(1-\beta\theta_p)(1-\alpha)}{1-\alpha+\varepsilon\alpha} \sum_{j=0}^{\infty} (\beta\theta_p)^j E_t mc_{t+j} \\
&\quad - \frac{(1-\beta\theta_p)\alpha}{1-\alpha+\varepsilon\alpha} \sum_{j=0}^{\infty} (\beta\theta_p)^j E_t \widehat{k}_{t+j}(i),
\end{aligned}
\tag{A1}
$$

$$
\begin{aligned}
\widehat{k}_{t+1}^*(i) &= \sum_{j=1}^{\infty} (\beta\theta_k)^j E_t \Delta k_{t+j+1} - (1-\beta\theta_k)\varepsilon \sum_{j=0}^{\infty} (\beta\theta_k)^j E_t \widehat{p}_{t+j+1}(i) \\
&\quad + (1-\alpha)(1-\beta\theta_k) \sum_{j=0}^{\infty} (\beta\theta_k)^j E_t ms_{t+j+1} \\
&\quad - \frac{(1-\alpha)(1-\beta\theta_k)}{(1-\beta(1-\delta))} \sum_{j=0}^{\infty} (\beta\theta_k)^j E_t \{i_{t+j} - \pi_{t+j+1} - \rho\},
\end{aligned}
\tag{A2}
$$

where $\widehat{P}_t(i) \equiv \frac{P_t(i)}{P_t}$ and $\widehat{K}_t(i) \equiv \frac{K_t(i)}{K_t}$ denote, respectively, firm i's relative price and relative to average capital stock as of time t. Moreover, we have used the definitions $\widehat{P}_t^*(i) \equiv \frac{P_t^*(i)}{P_t}$ and $\widehat{K}_t^*(i) \equiv \frac{K_t^*(i)}{K_t}$. Second, we posit rules for price setting and for investment:

$$
\widehat{p}_t^*(i) = \widehat{p}_t^* - \tau_1 \widehat{k}_t(i),
\tag{A3}
$$

$$
\widehat{k}_{t+1}^*(i) = \widehat{k}_{t+1}^* - \tau_2 \widehat{p}_t(i),
\tag{A4}
$$

where τ_1 and τ_2 are unknown parameters and $\widehat{p}_t^*$ and $\widehat{k}_{t+1}^*$ denote, respectively, the average newly set price and the average newly chosen capital stock. Third, we invoke the Calvo assumption for the price setting lottery and combine it with the definition

of the price index. This results in:

$$\pi_t = \frac{1 - \theta_p}{\theta_p} \widehat{p}_t^*. \tag{A5}$$

Fourth, we invoke the Calvo assumption for the investment lottery and combine it with the definition of aggregate capital, which allows us to write:

$$k_{t+1} = k_t + \frac{1 - \theta_k}{\theta_k} \widehat{k}_{t+1}^*. \tag{A6}$$

Therefore, we find:

$$\begin{bmatrix} E_t \widehat{p}_{t+1}(i) \\ E_t \widehat{k}_{t+1}(i) \end{bmatrix} = \mathbf{A} \begin{bmatrix} \widehat{p}_t(i) \\ \widehat{k}_t(i) \end{bmatrix},$$

where

$$\mathbf{A} \equiv \begin{bmatrix} 1 & \tau_1 (1 - \theta_p) \\ 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} \theta_p & 0 \\ -(1 - \theta_k) \tau_2 & \theta_k \end{bmatrix},$$

and stability requires that both roots of $\mathbf{A}$ are inside the unit circle. Next, we determine the remaining conditions for the unknown coefficients.

Law of motion of aggregate capital

We use the price-setting rule (A3) to substitute for the infinite sum $\sum_{j=0}^{\infty} (\beta\theta_k)^j E_t \widehat{p}_{t+j+1}(i)$ in (A2). The result is shown in the next equation:

$$\begin{aligned} \psi \widehat{k}_{t+1}^*(i) &= \psi \sum_{j=1}^{\infty} (\beta\theta_k)^j E_t \Delta k_{t+j+1} - \frac{\theta_p (1 - \beta\theta_k)\varepsilon}{1 - \beta\theta_p\theta_k} \widehat{p}_t(i) \\ &+ (1 - \alpha)(1 - \beta\theta_k) \sum_{j=0}^{\infty} (\beta\theta_k)^j E_t ms_{t+j+1} \\ &- \frac{(1 - \alpha)(1 - \beta\theta_k)}{(1 - \beta(1 - \delta))} \sum_{j=0}^{\infty} (\beta\theta_k)^j E_t (i_{t+j} - \pi_{t+j+1} - \rho), \quad \text{(A7)} \end{aligned}$$

where $\psi \equiv 1 - \frac{\tau_1(1-\theta_p)\varepsilon}{(1-\beta\theta_p\theta_k)}$. Averaging the last equation over all investing firms and

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subtracting the resulting equation from (A7) we can write $\widehat{k}^*_{t+1}(i)$ as a function of $\widehat{k}^*_{t+1}$ and $\widehat{p}_t(i)$, as in the investment rule (A4). This allows us to impose the following restriction on parameter τ_2:

$$\tau_2 = \frac{\theta_p(1 - \beta\theta_k)\varepsilon}{1 - \beta\theta_p\theta_k - \tau_1(1 - \theta_p)\varepsilon}. \tag{A8}$$

In order to derive the law of motion of capital, we aggregate (A7) over all investing firms and use (A6). This way we obtain:

$$\Delta k_{t+1} = \beta E_t \Delta k_{t+2} + \frac{1}{\eta_l}\left\{(1 - \beta(1 - \delta))E_t ms_{t+1} - (i_t - E_t\pi_{t+1} - \rho)\right\}, \tag{A9}$$

where $\eta_l^{-1} = \frac{(1 - \theta_k)(1 - \beta\theta_k)}{\theta_k}\frac{(1 - \alpha)}{(1 - \beta(1 - \delta))}\frac{1}{\psi}$.

Inflation equation

We derive the inflation equation in an analog manner. Combining the log-linearized first-order condition for price setting (A1) with the investment rule (A4) we find:

$$
\begin{aligned}
\phi\widehat{p}^*_t(i) &= \phi\sum_{j=1}^{\infty}(\beta\theta_p)^j E_t\pi_{t+j} + \frac{(1 - \beta\theta_p)(1 - \alpha)}{1 - \alpha + \varepsilon\alpha}\sum_{j=0}^{\infty}(\beta\theta_p)^j E_t mc_{t+j} \\
&\quad - \frac{(1 - \beta\theta_p)\alpha}{1 - \alpha + \varepsilon\alpha}\frac{1}{1 - \beta\theta_p\theta_k}\widehat{k}_t(i),
\end{aligned}
\tag{A10}
$$

where $\phi \equiv 1 - \frac{\alpha(1 - \theta_k)\beta\theta_p\tau_2}{(1 - \alpha + \varepsilon\alpha)(1 - \beta\theta_p\theta_k)}$. Next, we average the last equation over all price setters and subtract the resulting equation from (A10). After invoking the price-setting rule (A3) we can impose the following restriction on parameter τ_1:

$$\tau_1 = \frac{(1 - \beta\theta_p)\alpha}{(1 - \alpha + \varepsilon\alpha)(1 - \beta\theta_p\theta_k) - \alpha(1 - \theta_k)\beta\theta_p\tau_2}. \tag{A11}$$

Equations (A8) and (A11), when combined with the two stability conditions, de-

termine the two unknown parameters τ_1 and τ_2 Last, we use (A5) and derive the inflation equation by averaging (A10) over price-setters. This results in:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa_l \ mc_t, \tag{A12}$$

where $\kappa_l \equiv \frac{(1-\theta_p)(1-\beta\theta_p)}{\theta_p} \frac{(1-\alpha)}{(1-\alpha+\varepsilon\alpha)\phi}$.

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